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Performance and Measurements of the Fermilab Booster

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Performance and Measurements of the Fermilab Booster

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Abstract. We will describe measurements of the beam in the Fermilab Booster during the first five milliseconds. Most of the particle losses in the Booster are over after the first few milliseconds. At high intensity of 4×10^{12} the transmission is 75%. Such high beam loss can be a limiting factor for future high repetition rate operation of the Booster. The evidence, although indirect, suggests that the losses are the result of incoherent space-charge effects at low energy.

INTRODUCTION

The Booster was designed [1] in the 1960's with a 200 MeV proton linac as injector. Since 1978 multi-turn H^- injection is used to build up the beam intensity in the Booster [2]. The critical parameters which limit the luminosity in the Tevatron Collider are the beam emittances and the number of particles at collisions. Thus in the Collider era Booster performance was no longer judged simply by how many protons can be accelerated but by what density of particles can be delivered. The suspected cause of the emittance growth during the first few milliseconds after injection in the Booster was the tune spread caused by space charge [3] and errors in the magnetic guide field. Thus in 1993 the Linac energy was upgraded to 400 MeV [4]. The result of the upgrade is seen all the way to the Tevatron, an increase in the phase space density at collisions, Fig.1. Improvement in beam phase space density delivered from the Booster has also relieved some of the aperture problems present in the Main Ring and allows us to accelerate and deliver a significantly larger quantity of protons onto the antiproton target. This has resulted in 50% increase in the antiproton production rate, thus increasing the luminosity in the Tevatron Collider.

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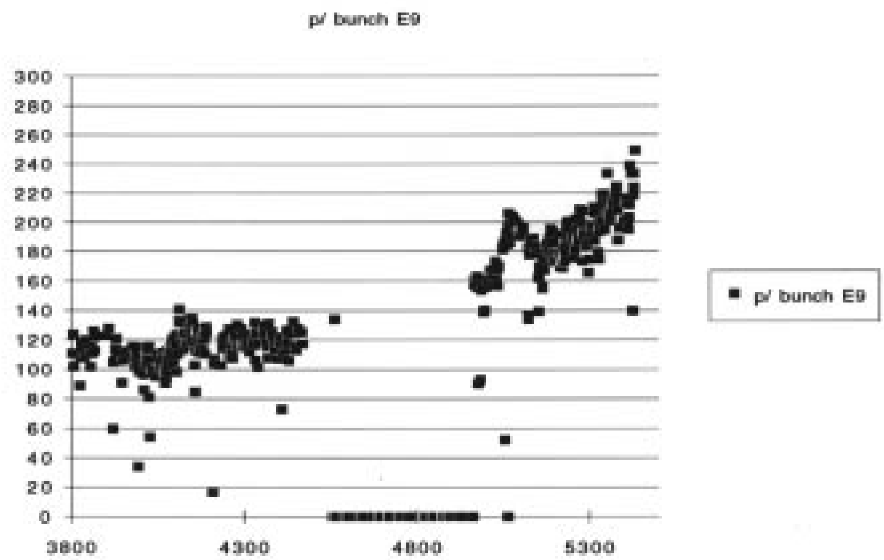

FIGURE 1. Proton intensity at collisions: The zero intensity points divide stores before and after the Linac upgrade.

OVERVIEW

The Fermilab Booster [5] is a rapid-cycling, 15 Hz, alternating-gradient synchrotron with average orbit radius of 75.47 meters. It accelerates protons from 400 MeV, the kinetic energy of the Linac beam, to 8 GeV, the nominal injection kinetic energy of the Main Ring/Main Injector. The lattice consists of 96 combined-function magnets in 24 periods. The nominal horizontal and vertical tunes are 6.7 and 6.8. The revolution time at injection is 2.2 μs. The linac delivers peak-current of 45 mA and the transfer line to the Booster usually runs with 98% transmission efficiency. Usually up to ten turns of H^- beam is injected. During injection a pulsed orbit bump magnet system is used to superimpose the trajectories of circulating and injected beam. The beam is accelerated with 17 rf cavities, transition gamma of the ring is $\gamma_t = 5.445$ and harmonic number of the ring is $h = 84$.

MEASUREMENTS

Many effects determine the behavior of the beam in the Booster at injection: the linac beam energy, the energy spread, the beam transverse emittances, and injection mismatch. In addition, the Booster has no "porch" at injection, the main magnetic field oscillates sinusoidally at 15 Hz and DC beam must be "adiabatically" captured in rf buckets fairly quickly. All these effects are mixed with effects coming from nonlinear field errors and significant remanent sextupole field at injection. In order to determine the relative contribution of all of these effects on the beam loss we have measured and vary most of these parameters one at a time around their

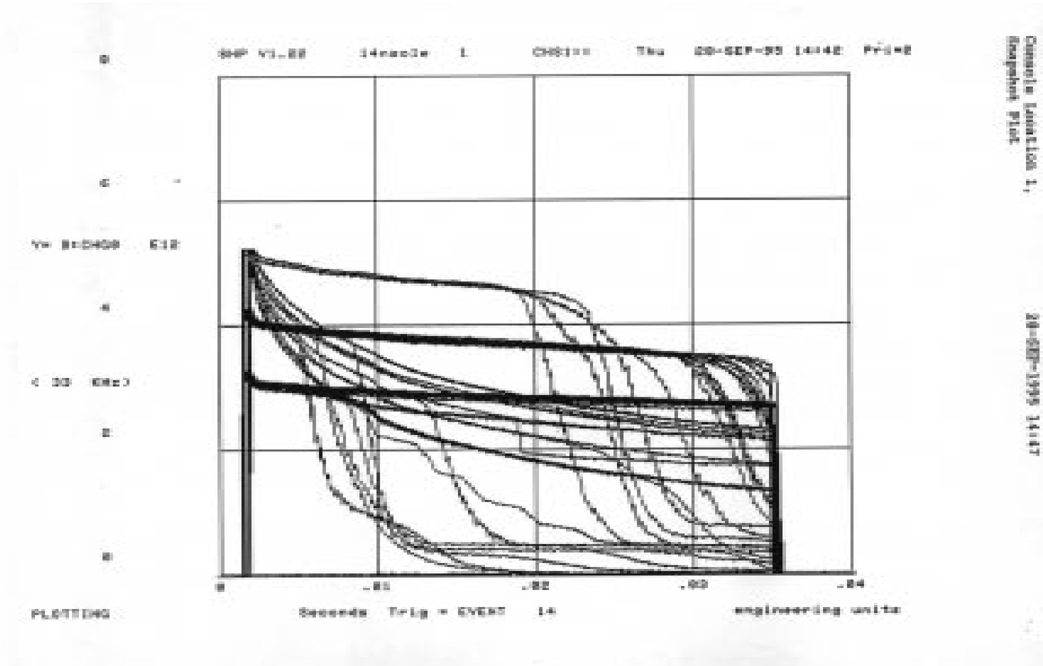

FIGURE 2. Booster DC at 400 MeV, RF on. More than 5.3E12 protons for 20 msec.

design/nominal values.

Injection Energy and Energy Spread

The Linac output energy is measured in two different ways, using a spectrometer magnet at the end of a diagnostic line and Phase-Scan method [6] which fixes the phase and amplitude of the accelerating modules to their design values. The output energy is 401.5 MeV with error less than ± 1.8 MeV. The absolute value of the output energy of the linac is not a critical parameter for Booster operations because B_{min}, the minimal value of magnetic field, can be easily adjusted. The critical parameters are energy variations during the linac pulse and from pulse to pulse. Energy variations during the linac pulse are monitored in the diagnostic line after a 40 degree bend. The signal from a beam position monitor is digitized using 2 MHz quick digitizer and displayed using linac control system. Variation of the position of the beam from beginning to end as well from pulse to pulse translates to energy variation of $\frac{\Delta T}{T} = 0.2\%$. The stability of the Linac beam energy from pulse to pulse is also monitored using the phase of the beam-induced rf signal at a strip line detector 10-meters upstream of the injection to the Booster, right before the Debuncher. The role of the Debuncher is to minimize energy spread of the beam coming from the Linac and to correct for any energy variation from head to tail and from pulse to pulse of the injected beam. The phase and amplitude of the Debuncher are adjusted with a feed forward system to be flat during beam time. To measure the energy spread inside the 200-MHz bunches we have set the Booster to DC mode keeping it at 400 MeV and turning off all rf cavities. By injecting $\sim 90\%$ of a single full turn into the Booster we were able to measure turn

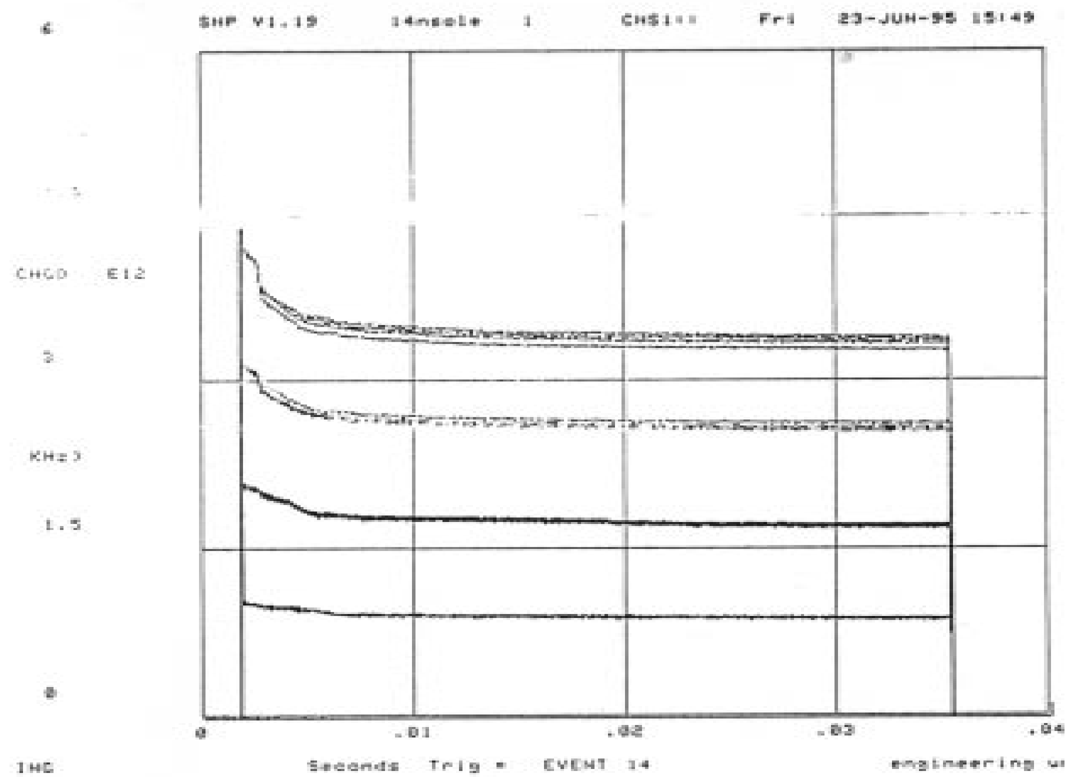

FIGURE 3. Charge vs. time(msec) for whole Booster cycle, 2, 4, 6, and 8 turns injected. There are two type of losses clearly visible in the first 5 msecs.

by turn energy spread of any particular bunch. We found that the Debuncher can be adjusted to keep total energy spread to be as low as $\frac{\Delta T}{T} < 3.0 \times 10^{-3}$ for 95% of the beam. We have measured energy spread only for the first few turns. Injected beam normally passes through the stripping Carbon foil about ten to twenty times. We have estimated that injected protons lose $\sim$ 60 eV per foil passage and that the energy spread introduced by the foil in normal operations is negligible. Energy spread due to multiple scattering has not been measured.

Injected Transverse Emittances

All the measurements and simulations of the beam coming out from the Linac indicate that transverse emittances are less than 6 π mm-mrad. Here and throughout this paper, the normalized emittances containing 95% of the beam are quoted and units of mm-mrad are used. A Gaussian transverse distribution of rms width σ, observed at a location where the dispersion is zero and the lattice amplitude function is β_L corresponds to a normalized, 95%, emittance ϵ_N given by

$$\epsilon_N = \frac{6\pi\beta\gamma\sigma^2}{\beta_L}.$$

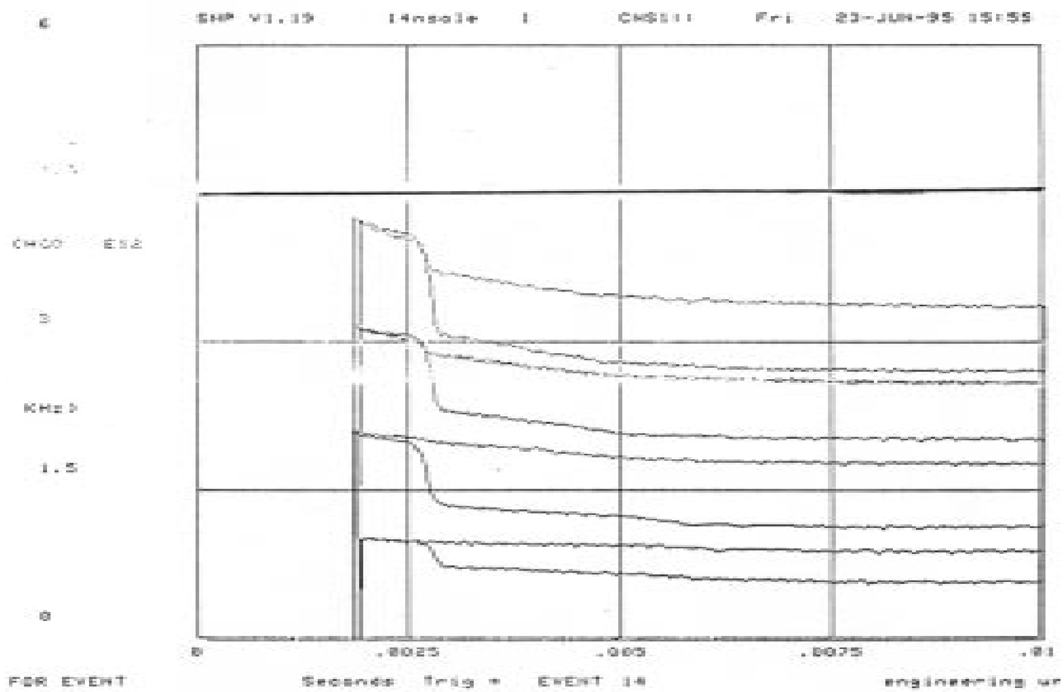

FIGURE 4. Beam intensity in the first 8 msecs for 2, 4, 6, and 8 turns injected with Debuncher on and off.

At the end of the Linac, emittances are measured using three wires with no focusing element in between. In the transport line between Linac and Booster, beam profiles are measured using multiwires for different settings of the quadrupoles upstream of each wire. The emittances are extracted using Trace3d code.

At injection the emittance growth due to the Coulomb scattering on the $\frac{200\mu g}{cm^2}$ Carbon stripping foil can be estimated from multiple-scattering theory. The calculated result is an increase of normalized emittance of 0.03π in horizontal plane and 0.11π in vertical plane per foil crossing, assuming no coupling during injection. This effect was not measured; transverse mismatch between injected beam and machine lattice hides the effect of the foil.

RF Capture Process

If the Booster accelerating cavities are all turned on at a sufficiently low gap voltage to cause good adiabatic capture, it is known that some of the cavities will suffer from electron multipactoring, subsequently inhibiting further increase in voltage. To avoid this all the cavities are turned on before injection but with pairs of cavities out of phase ("paraphased") so that the net accelerating voltage is small. When voltage is required the cavities are brought into phase by a "paraphase program" which allows optimum capture. It is apparent that this rf turn-on procedure can be done in a large variety of ways, and the manner in which the beam responds to these variations is not always obvious. Among the rapidly variable parameters that

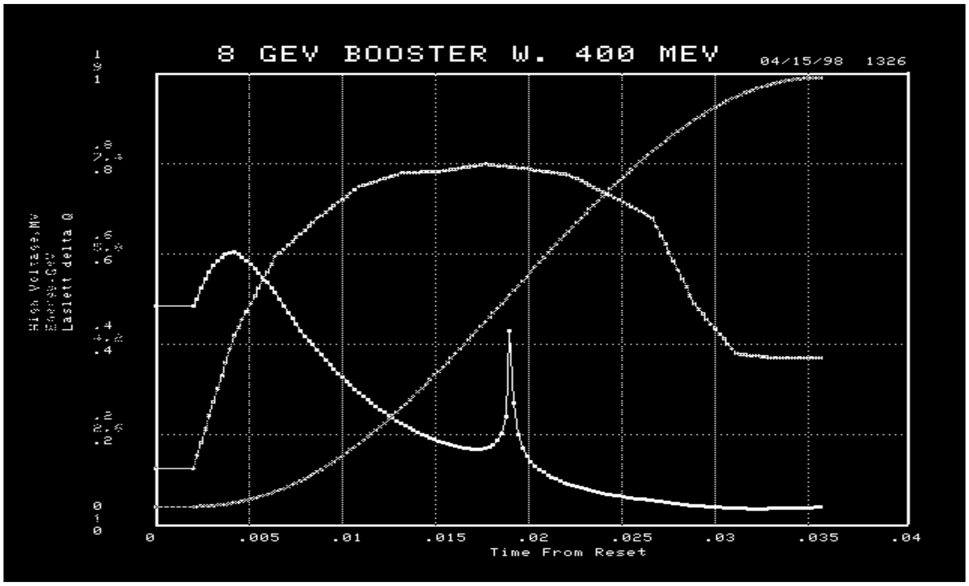

FIGURE 5. The Booster rf voltage, energy and Laslett tune shift. Note that the tune shift is larger than the injection value for the first 5 msec of beam.

affect capture are; injection time, minimum value of magnetic field, amplitude and phase of Debuncher rf voltage, the initial value of the Booster rf frequency program, the initial value of the rf amplitude program and the parameters of the paraphase program. The paraphase program was derived from the longitudinal tracking program ESME which includes longitudinal space charge effects. The starting time and the level of the starting voltage were "tuned" for best capture. Figure 3. shows the beam intensity in the Booster in the first 8 msecs, for 2, 4, 6, and 8 turns injected, with the Debuncher on and off. The first fast loss is the beam not captured in the rf bucket. This type of beam loss can be avoided with adjustment of the Debuncher. In operations, the starting time and the level of the starting voltage are "tuned" for best transmission and optimal loss pattern.

Slow Loss

A second type of losses clearly visible in Figures 2 and 3, which we call slow losses, are always present and "impossible" to tune out. We believe that these losses are related to the Laslett tune shift of the beam. Figure 5. [7] shows Booster rf voltage, energy and Laslett tune shift during the Booster cycle. The Laslett tune shift is calculated according to the formula

$$\Delta\nu_{sc} = \frac{3r_0 N_{tot}}{2B\beta\gamma^2\epsilon_N}$$

where r_0 is the proton radius, N_{tot} total number of protons in the ring, ϵ_N normalized 95% emittance, and B the ratio of the average to the peak circulating current. The bunching factor, B, is calculated under the assumption that the bunch shape is Gaussian. Figure 5. shows that the Laslett tune shift stays above the tune shift at injection for more than 5 msecs after injection, about the time that the slow loss

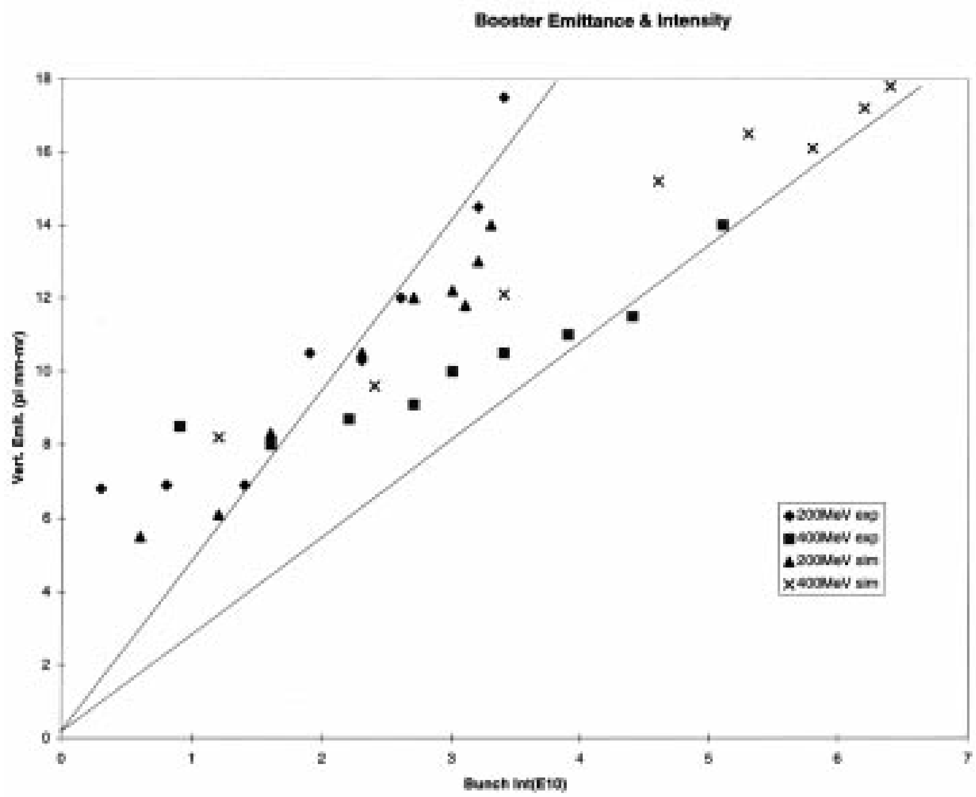

FIGURE 6. Vertical Emittance as function of bunch intensity

pattern is present. In support of this interpretation we present measurement and simulation of vertical emittances for 200 MeV and 400 MeV injection energy to the Booster. The simulation results are taken from Steven Stahl's Ph.D. thesis [8] and include effect of gradient errors, steering errors, chromaticity and space charge.

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